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Forecasting Grain Weight Per Corn Ear On August 1

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ABSTRACT

August 1 forecasts of corn grain weight per ear from models using daily weather observations for the ten-State corn objective yield survey region from 1979 through 1986 had a 36 percent smaller root mean square error than the corresponding operational survey forecasts. The weather data used in these models are daily temperature and soil moisture indices aggregated over five weekly periods, with four periods occurring prior to and one period after the median silking date for the individual state and year. These models were developed from 1967-83 data (excluding 1970) and evaluated from 1972 through 1986.

Since these models show substantial potential for considerably more accurate August 1 corn forecasts than does the present procedure, a semi-operational test in four major corn producing states is recommended for 1988.

KEY WORDS

Corn, forecast, corn ear grain weight, crop calendar, weather model

ACKNOWLEDGMENT

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FORECASTING WEIGHT OF GRAIN PER CORN EAR USING CROP CALENDAR/WEATHER MODELS

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Paul W. Cook

SUMMARY

August 1 forecasts of corn grain weight per ear from models using daily weather observations for the ten-State corn objective yield survey region from 1979 through 1986 had a 36 percent smaller root mean square error than the corresponding operational survey forecasts. The weather model August 1 forecasts also had a 17 percent smaller root mean square error than did the September 1 forecasts from the operational program. If these results hold up under further testing in 1988, then it seems that the addition of daily weather data to the current corn forecasting system could substantially improve U.S. August 1 corn forecasts. A semi-operational test of these procedures in four of the ten corn objective yield survey states is recommended for the 1988 season.

These models were developed from 1967-83 data (excluding 1970) and are based upon seven-day aggregations of daily temperatures and soil moisture indices. These aggregations were defined with respect to the median silking dates for the individual state and year. Temperature values used included degree days greater and less than 88°F, average daily temperatures, and the difference between the daily minimum and maximum temperatures.

The principal requirement for implementing these weather models in the NASS operational corn objective yield survey program will be to establish procedures with the National Oceanic and Atmospheric Administration (NOAA) for obtaining reports from the NOAA cooperative weather stations in a timely manner.

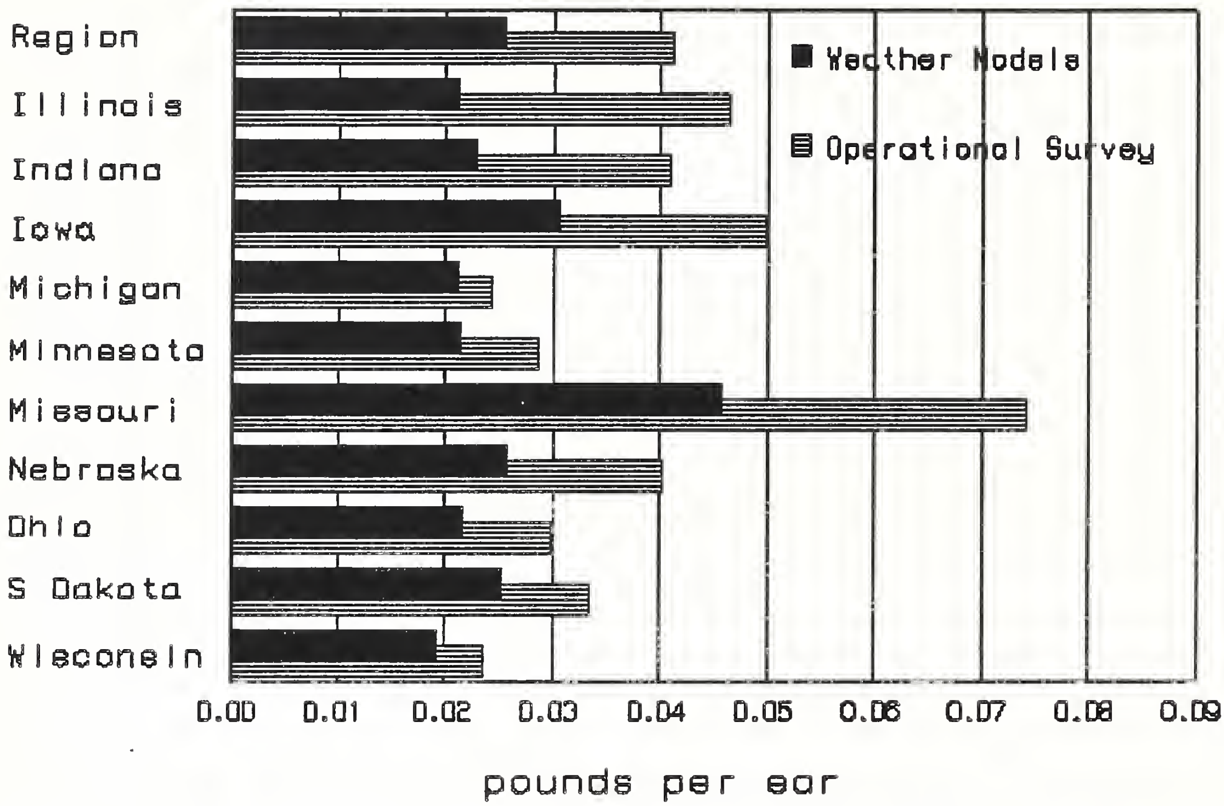

Figure 1: Root Mean Square Forecast Errors, Weather Models and Current August 1 Forecasts.

INTRODUCTION

The purpose of this study was to use daily weather data obtained prior to August 5 in regression models to improve the August 1 forecast of grain weight per corn ear. Currently, in each of the corn objective yield (COY) States[1], NASS uses the average final weight of grain per ear from the previous five years to predict the August 1 ear weight for samples which have not reached the 'blister' stage of development. Ear grain weights for samples which have at least reached the 'blister' stage of maturity are predicted from models which relate the average length of ear (measured over the husk) and the average length of kernel row to final ear weight. This procedure would work well if ear weights changed little during the six year period. Unfortunately, year to year fluctuations in ear weight are common. Also, Missouri is normally the only State where even a few sampled corn fields have progressed to the 'blister' stage of development by the last week of July (the period of the NASS August 1 survey). Therefore the predicted weight of grain per ear is the major source of error in forecasting corn yields.

Factors affecting the corn grain weight per ear are the number of kernels per ear and the average weight per kernels. In the region covered by this study, only the number of kernels per ear would be affected by weather prior to August 1. Therefore the necessary premise of this study is that soil moisture and temperature related stresses from shortly before tasseling to shortly after silking are critical in determining the maximum number of kernels that can develop. Such stresses would usually result from high temperatures although the effect of high temperatures may be modified by sufficient soil moisture. (Runge, 1968)

Different sources disagree as to the relative importance of soil moisture. For example, Stapper and Arkin (1979) cite Salter and Goode (1967) and Slabbers (1979) as having determined that water stress during the pollination period is the most important reason for grain yield decrease. On the other hand, Runge (1968) commented that higher than normal temperatures (90 to 95^{o}F) may not be harmful to corn if adequate moisture is available. Runge also found that the maximum effect of temperature and rainfall on corn yield occurs over a two week period. (It could also be argued that a major function of an 'adequate' supply of soil moisture is to function as a heat sink for moderating excessive temperatures within a corn field.)

In contrast to the relatively minor effects of differing levels of soil moisture, the effects of temperature fluctuations on photosynthesis are quite dramatic. Photosynthesis starts at

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1 Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Nebraska, Ohio, South Dakota, and Wisconsin.

about 58°F, peaks at 86°F to 90°F, and then declines rapidly. Reduced rates of photosynthesis would result in reduced supplies of photosynthate for ear and kernel development. Extremely high temperatures could also require a greater water supply than was available.

This study operated under the following constraints.

1. The dependent variables are the state average final estimates of grain weight per ear from the COY surveys. Therefore, all independent variables must also be computed at the State level.
2. The series of reliable estimates for corn ear weights starts in 1967; however, data for 1970 was excluded because of the Southern corn leaf blight epidemic in that year.
3. The median planting, silking, and ripening dates required by this study were derived from NASS State Statistical Office records. For several states, these records were available only from 1970 or 1973.

A review of the literature did not reveal any previous attempts to forecast weight of grain per ear for a large area using weather data. However, there have been many attempts to predict corn yields from observed weather phenomena using two basic modeling approaches, 'statistical' and 'plant process'. Statistical models attempt to correlate combinations of observed weather events with average yields over a large area, at the field level, or at the plot level. Typically, statistical models have used aggregations of weather events over a month or more. Most statistical models have also assumed that planting, tasseling, silking, and ripening occur at the same times each year, and have assumed that the impact of 'improved technology' could be approximated by a (piece-wise) linear trend.

The second approach, plant process modeling, examines crop growth stages and weather conditions at the plot or plant level and uses deterministic rate equation models to mimic how the plant will grow. Plant process models utilize daily or hourly weather observations, detailed information about a particular site, and information about the plant genotype to 'grow' a representative plant from seeding to maturity for that site. This approach requires very detailed data such as soil types, method of land preparation, variety and date of planting, amount and timing of fertilizer applications, daily precipitation and temperatures, and type of weed control for each site. Until the time this study began, neither approach had been successful in producing yield prediction models which were good enough to warrant adoption by NASS.

Because of the data constraints listed above, the statistical approach to modeling was used in this study. However, the availability of daily weather, and of median planting and silking dates

for each state made possible the use of weekly aggregations of weather variables which were referenced to a critical stage of corn ear development (silking) rather than to an arbitrary calendar.

This report includes a literature review, descriptions of the data, descriptions of the variable computation, documentation of the model development procedures, and results from evaluations of selected models.

METHODOLOGY

Data: The types and sources of data used in the developmental portion of this study were:

(a) The dates, by years (1967-83)[2], at which 50% of the corn crop in each state was planted and had silked. These two dates were derived from the Weekly Crop-Weather surveys conducted during the growing season by NASS's State Statistical Offices for these states.

(b) Station level weather data (daily maximum and minimum temperatures, and precipitation), obtained from both first order and cooperative stations, 1966-83, as compiled by the Oklahoma Climatological Survey from the NOAA TD3200 weather files.[3]

(c) NASS corn objective yield survey August 1 forecast and final weights of grain per ear, by state.

(d) NASS estimates of acreage harvested for grain, by CRD's, 1967-83.

Corresponding data for 1984-86 were subsequently obtained for the evaluative portion of the study. Except for the 1985-86 weather data, which was obtained directly from the NOAA National Climatic Weather Center at Asheville, NC, this data came from the same sources as from previous years.

Based on the literature search, the median silking date was selected as a reference point for aggregating the weather data. Three different length periods of weather aggregations, (5, 7, and 14 days), and several combinations of weeks before and after silking were examined. The most information was contained in weekly aggregations of weather data within the period from four

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2 Two states, Michigan and Minnesota, were unable to provide crop progress data from 1970 and 1973, respectively. Also, 1970, the corn blight year, was excluded from this study for most States as representing a condition which is not expected to recur.

3 There were at least 100 such stations per State (Appendix Table A-3)

weeks before silking to one week after silking. The second week after silking often explained even more about the final ear weight but this data is likely to be unavailable at the time of the August 1 forecast.

The procedure used in this study was to:

(a) construct daily CRD and state (weighted by CRD acres harvested) level estimates of precipitation, minimum temperature, maximum temperature, and average temperature from individual weather station reports;

(c) construct large area estimates of daily water consumption utilizing a modification of the Blaney-Criddle method (see Appendix) and the estimated dates by which 50 percent of the crop was planted and had silked;

(d) construct daily estimates of the amount of remaining soil moisture[4];

(e) compute weekly averages of the following weather derived types of variables: soil moisture balance, average temperature, maximum temperature, the difference between daily minimum and maximum temperatures, and the amount (degree days) by which the daily maximum temperature exceeded or failed to reach 86, 88, and 90 degrees Fahrenheit thresholds[5];

(f) compute average daily rates of change in levels of soil moisture during periods of two to five weeks, beginning four weeks before the 50 percent silking date; and

(g) compute the interaction of soil moisture with the degree days in excess of and below the 88°F threshold value;

A soil moisture index was used rather than precipitation because (a) total precipitation during a particular period only indicates how much precipitation occurred, not how much water was available; (b) moisture requirements are dependent upon temperature; and (c) the use of a cumulative variable such as soil moisture tends to average out the potentially undesirable effects of a sometimes sparse weather station network. The Blaney-Criddle method was used to compute the soil moisture indices because (a) it is crop specific, (b) it is geared to the crop calendar, and (c) it does not require detailed soil parameters. Two potential disadvantages of the Blaney-Criddle method are that it does not consider the location of water in the soil profile and it disregards the possibility of moisture loss through deep percolation and runoff.

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4 The soil moisture balance computations assumed a maximum soil water holding capacity (in the corn root zone) of 10.0 inches.

5 Thresholded daily temperatures were computed as follows:

'Degree days > threshold' = max[0,(maximum - threshold)]

'Degree days < threshold' = max[0,(threshold - maximum)]

Non-weather derived variables also considered in this study included the State median completion dates for planting and silking, the amount of time between these dates, the number of stalks per acre, and trend.

<u>Model Development:</u> The first step in model development was to review the linear correlations of the independent variables to each other and final COY estimate of corn ear weight. These correlations were reviewed to eliminate those variables which showed no appreciable correlation with ear weight, and to determine which independent variables were highly collinear. (A high degree of collinearity between many of the weather derived variables was expected. This is because (a) temperatures and soil moisture indices during one day or week tend to be like those in previous or succeeding days or weeks, and (b) many of the variables described above are based on data which are subsets of data used in other variables.)

The review process eliminated all of the non-weather variables except the median silking date, and even that could be disregarded in most states. (Trend, a major factor in almost all corn <u>yield</u> models, was found to be highly correlated with plant population but not with weight of grain per ear.) In addition, the maximum daily temperatures were less well correlated with final weight of grain per ear than were the degree days calculated for the 86, 88, or 90 degree Fahrenheit thresholds. Three thresholds were examined since the literature did not uniquely specify one value.

Although the intent of this study was to develop ear weight forecast procedures from weather prior to about August 1, correlations with final ear weight were computed for weekly weather variables from four weeks before to five weeks after the median silking date for each year. These correlations identified three periods of time where at least one of the weather variables were highly correlated to final ear grain weight. These periods were two to three weeks before silking, one to two weeks after silking, and four to five weeks after silking. These time periods would correspond roughly to those for early ear development, initiation of kernel development, and of kernel filling. Variables from the first time periods would always be available for an August 1 forecast, variables from the second time period would usually be available in all but South Dakota, Minnesota, Wisconsin, and Michigan. Variables from the last time period would only be available for a September 1 forecast model. Fortunately, the highest correlations were found for variables from the first two time periods.

Correlations for maximum degree days in excess of 90^{o}F thresholds generally were inferior to those maximum degree days for 86^{o}F and 88^{o}F, and correlations for thresholded maximum degree days below 86^{o}F were lower than for maximum degree days below 88^{o}F and 90^{o}F.

Although the correlations for 88°F threshold were not always best, they were always competitive so the 88°F threshold was selected to simplify analysis.

The types of variables considered further in the analysis were weekly soil moisture indices, average temperatures, differences between minimum and maximum temperature, and cumulated degree days below and above the 88°F threshold. Products of the weekly soil moisture indices with the degree days variables were also used. Plots of the independent variables and obvious transformations of those variables did not identify any marked deviations from linearity. In each State, the linear correlations to final ear weight were then used to select variables for further analysis. Variables were selected when the probability that the correlations were different from zero was at least 0.6.

All possible models for one, two, and three variable combinations of the candidate variables were considered. These models were evaluated in the following manner.

1. A two or three variable model was determined to be acceptable if adding the second (or third) variable resulted in a significant (at the 95 percent level of probability) reduction in the SSE (Error Sum of Squares).

2. The acceptable models which had the highest adjusted coefficients of determination (AdjR^2) and which did not include highly collinear variables were subjected to a censored jackknife procedure (jackknife), from 1972 through 1983. Forecasts for each year were computed using model coefficients computed from all other years of data. Model predictions were censored and not allowed to be smaller than the second smallest final ear weight during the study period, nor larger than the second largest. The results of this procedure were compared with the actual COY August 1 forecast and final ear weights. Evaluation statistics generated from this procedure included the means of the absolute and relative errors and the standard deviation of the forecast errors for both forecasts, the Residual Sum of Squares (RSS) from the actual model fit, the Predicted REsidual Sum of Squares (PRESS) for the model over the evaluation period, and an F statistic to test the hypothesis that any observed reduction in the standard deviation of the model forecast errors could have occurred by chance. The acceptable models were then ranked according to their respective AdjR^2, F, RSS, and PRESS statistics.

The decision hierarchy for selecting the recommended models was: (a) the rankings of the models (as defined above), (b) an appreciable difference (at least 10 percent) between the PRESS statistics, (c) input from the greatest number of weekly periods, and (d) conformity of the model variables to neighboring states.

Three types of models were selected. These were:

1. a model using no soil moisture variables,

2. a model using at least one soil moisture variable, and
3. a 'late growing season' model for which data would always be available in time for use in an August 1 forecast.

These criteria are both logical and practical. A model which uses soil moisture requires precipitation and temperature data from about May 1. However, a model that does not use soil moisture variables requires only temperature data from about four weeks before the median silking date. Therefore, it would be desirable, in terms of a reduced data collection effort, if non-soil moisture models could be used without much loss in predictive accuracy. Finally, a model for which weather data will always be available, even in years when the growing season is late, must be available.

The specific models selected for operational use were then subjected to a simulated operational evaluation (bootstrap). In this evaluation, forecasts were generated for each year from 1979 through 1986 using only weather data that would have been available by August 5, and model parameters which were calculated only from weather data from previous years. This procedure provides assurance that forecasts would operate properly in years which were not used in selecting the models (1984-86) and documents a historic series of predictions for NASS State Statistical Office and Estimates Division use. Also, simple averages of the forecasts from each of the three types of models were used to create a more robust 'composite' forecast.

<u>Median silking dates:</u> The distribution of median silking date (SILK_DAY) over time for a state is important because it indicates (1) the likely periods that weather data would be available for an August 1 forecast,[6] and (2) the likelihood that median silk date must be forecast from incomplete data. The occurrence of median silk date influences the choice of forecast models because NASS is committed to issuing its initial forecast of corn yield on about August 10. Collection of weather data (and estimation of the median silking day) must stop by August 5 to allow sufficient time for data collection, processing, and analysis before the forecast is issued. For example, a median silk date of July 29 or earlier would indicate that weather data for the seven day period immediately after the median silk date probably would be available for the August 1 forecast.

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6 Typically, data for a NASS August 1 forecast is summarized between August 2 and August 8, and released on August 10.

Figure 2. Median silking dates, by states, 1967-86.
Legend: A = 1 obs, B = 2 obs, etc.

```
STATE +------+------+------+------+------+------+----+
      |      |      |      |      |      |      |    |
  IL  +     A|    A B AB  BAD AA A|      |      |    |
  MO  +      | A  A A AA A BBA BA |A A   |   A  |    |
  IA  +      | A    |   AB ABBAAC AB    |      |    |
  NE  +      |     A|     ACBABB AAA AA  |      |    |
  IN  +      |      A AAA AA   BACA B A A|      |    |
  MN  +      |  A   |      |AB C  A AA A |      |    |
  OH  +      |      |   AAAABAA   C B D  |      |    |
  SD  +      |      |     A|   A BA CAABA|A     |    |
  WI  +      A      |      |  A  BAAAAAAB| BA   |    |
  MI  +      |      |      |     A|   CABBC AB A| A  |
      +------+------+------+------+------+------+-----
            Jul    Jul    Jul    Jul    Aug    Aug
             8      15     22     29     5      12
```

Median silking dates

As indicated in Figure 2, the occurrence of the median silking date varies widely, both between states and over years. For example, unusually early median silking dates were reported for Iowa in 1975, for Illinois, Nebraska, and Michigan in 1976, and for Missouri, Minnesota, South Dakota, and Wisconsin in 1977. Also, an unusually late median silking date was reported in Missouri in 1978. Historically, the earliest occurrence of median silk date within this study period was July 7, in Illinois, and the latest occurrence was August 14, in Michigan. States where the median silk date always occurred before August 5 were Illinois, Indiana, Iowa, Minnesota, Nebraska and Ohio. For the other four states, there is a possibility that the median silking date would need to be extrapolated from incomplete data.

RESULTS

The recommended models[7] differ in response to the differences in climatic regimes and growing seasons between the different states. However, there are certain similarities. For example, one or more of the closely related variables: degree days above 88°F for weeks 2 or 3 (DDG88F2, DDG88F3), average temperatures during weeks 2 or 3 (AVTEMP2, AVTEMP3), and the average difference between minimum and maximum temperatures during week 2 (DIFTMP2) appear in at least one model for all States except Missouri. In the westernmost states, temperatures in excess of 88°F are prevalent and overshadow the effects of the soil moisture indices. Also, in Missouri, extreme temperatures after the median silking date are so prevalent, and detrimental, that the impact of temperatures before the median silking date is obscured. In contrast, the more moderate climatic regimes in the easterly states typically led to an increased emphasis on the soil moisture indices and temperatures less than 88°F.

Weather data from the week after silking is required by at least one model in Iowa, Nebraska, and Ohio, and by all models in Missouri. Such models could be used only in those years when the median silking date is on or before July 29. For Missouri, two models require data from the second week after the median silking date.

During the eighteen year study period, data for the first week after silking would not have been available two times in Iowa, three times in Nebraska, and six times in Ohio. Data from the second week after silking would not have been available nine times in Missouri. Alternative models which do not use data from the missing weeks would be used in those years.

Root mean square forecast errors (RMSFE) from the regular objective yield survey August 1 forecasts, of the censored jackknife predictions (jackknife) of ear weight from 1972 through 1983, and of simulated operational (bootstrap) predictions from 1979 through 1986 are listed in Table 1. The relative gains (RG)[8] in efficiency of both the jackknife and bootstrap predictions are also listed. (Detailed regression diagnostic statistics, and output from the jackknife and bootstrap evaluations of these models is included in the companion publication, "Technical Notes: Forecasting Weight of Grain per Corn Ear Using Crop Calendar/Weather Models".)

The evaluation of the root mean square forecast errors considered the following factors.

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7 See Appendix Figure A-3.
8 RG = 1 - [(Model root mean square forecast error) / (August 1 COY root mean square forecast error)]

1. Comparisons of the best non-soil moisture models with those which require soil moisture.
2. Comparisons of the best models for each State with the actual COY August 1 forecasts for those years.
3. Determination as to what loss in potential predictive accuracy might result in those years when a late growing season requires use of the 'late growing season' models.
4. Determinations as to possible gains from use of the 'composite' forecasts.

The jackknife root mean square forecast errors from the 'no soil moisture' models (Model 1) were at least 10 percent smaller than those from the models using at least one soil moisture variable (Model 2) in two States, and at least 10 percent larger in four States. However the bootstrap RMSFE from the 'no soil moisture' models were at least ten percent smaller than those from the 'soil moisture' models in four States, and at least 10 percent larger in three. Notable swings in the RMSFE of the 'soil moisture' models occurred in Indiana (from .0215 to .0292), and Nebraska (.0160 to .0293). On the other hand, the 'no soil moisture' model for Michigan was clearly inadequate.

The 'soil moisture' model jackknife root mean square forecast errors for Michigan and Wisconsin were 47 and 36 percent smaller than those from the actual objective yield August 1 forecasts. However, the corresponding bootstrap RMSFE's were only 18 and 24 percent smaller. For Michigan, this decline in accuracy resulted in the inability of any of the models to predict the high 1984 final ear weight. For Wisconsin, all models had smaller RMSFE's during the bootstrap period but the RMSFE of the August 1 COY predictions were much smaller (final ear weights were much less variable). Therefore the relative gain from using the weather models was less.

Except for Ohio (31 percent), the relative gains (RG)[9] for the 'no soil moisture' model jackknife forecasts for the other eight States (excluding Michigan and Wisconsin) ranged from 53 to 57 percent. The corresponding relative gains for the bootstrap forecasts were more diverse, ranging from 17 percent (South Dakota) to 66 percent (Indiana). A major portion of the reduced gains in South Dakota, Minnesota, and Ohio resulted from decreased variability of final ear weights during the bootstrap evaluation period.

The penalty for using a 'late growing season' model varied by States but ranged from negligible to about a fifty percent reduction in the relative gain in forecast accuracy as compared to the preferred 'no soil moisture' or 'soil moisture' models.

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9 Relative gain = 1 - (model RMSFE)/(objective yield RMSFE)

As indicated above, neither the 'soil moisture' nor the 'no soil moisture' type models were always best in their performance during the two evaluation periods. This indicates that the performance of the models is somewhat data dependent. Therefore we formed a more robust estimator, a simple average (composite) of the individual model forecasts. As expected, the composite forecast was more consistent across evaluation periods although it was not quite as precise as any single model during any one evaluation period. Accordingly, a composite forecast from several selected individual models is recommended.

Table 1. Root mean square forecast errors (RMSFE) and relative gains (RG) for jackknifed (1972-83) and bootstrapped (1979-86) evaluations of the current procedure, the recommended models, and the composite forecasts.

State	Jackknife: Objective yield	Jackknife: Model 1[a] / Model 2[b] / Model 3[c] / Composite	Jackknife: RG	Bootstrap: Objective yield	Bootstrap: Model 1 / Model 2 / Model 3 / Composite	Bootstrap: RG
Illinois	.0509	.0233	.54	.0465	.0227	.52
		.0243	.52		.0203	.56
		.0259	.49		.0265	.43
		.0226	.55		.0211	.55
Indiana	.0562	.0264	.53	.0409	.0138	.66
		.0215	.62		.0292	.28
		.0211	.62		.0278	.32
		.0198	.65		.0228	.44
Iowa	.0569	.0260	.54	.0470	.0285	.41
		.0321	.44		.0333	.29
		.0386	.32		.0357	.24
		.0299	.47		.0306	.34
Michigan	.0338	.0278	.18	.0243	.0257	-.06
		.0179	.47		.0199	.18
		.0187	.45		.0207	.15
		.0219	.35		.0211	.13
Minnesota	.0533	.0249	.53	.0287	.0197	.31
		.0242	.54		.0206	.28
		.0264	.50		.0258	.10
		.0239	.55		.0214	.26
Missouri	.0763	.0351	.54	.0741	.0398	.46
		.0386	.49		.0446	.40
		.0428	.44		.0469	.37
		.0375	.51		.0458	.38
Nebraska	.0451	.0194	.57	.0402	.0213	.47
		.0160	.65		.0293	.27
		.0163	.64		.0332	.17
		.0151	.67		.0257	.36
Ohio	.0471	.0323	.31	.0299	.0235	.21
		.0203	.57		.0258	.14
		.0225	.52		.0265	.11
		.0215	.54		.0216	.28
South Dakota	.0662	.0292	.56	.0333	.0276	.17
		.0330	.50		.0358	-.07
		.0304	.54		.0272	.18
		.0280	.58		.0252	.24
Wisconsin	.0436	.0263	.40	.0236	.0205	.13
		.0280	.36		.0179	.24
		.0298	.32		.0195	.17
		.0277	.36		.0192	.19

[a] No soil moisture variables.

[b] At least one soil moisture variable

[c] Late season model

OPERATING COSTS

The major cost in operating these models will be that incurred in collecting the required daily weather data and putting it into computer readable form. The requirements are for daily reports of minimum and maximum temperatures and precipitation, from the start (about May 1) of the corn growing season each year to about August 5. Such reports should be obtained from at least two weather stations in each Crop Reporting District.

The availability of daily weather data of the type (minimum and maximum daily temperatures and precipitation) needed for these models within the 10-State objective yield survey region varies by State. For the 4-State area of Illinois, Indiana, Michigan, and Ohio, daily weather data from both the NOAA (National Oceanic and Atmospheric Administration) Class A (manned) and cooperative weather stations is collected daily by the NOAA Mid-East Regional Weather Center at West Lafayette, Indiana. This data was obtained for the Indiana weather stations in printed form by the Indiana State Statistical Office (SSO) of NASS and needed only to be keyed into NASS computer files. (This was for a pilot test of the weather models in 1987.) However, this data was already on the NOAA Mid-East Regional Weather Center computers so that it may be possible to transfer the data in electronic rather than printed form.

With the exception of Missouri, the cooperative weather stations in the remaining states file weekly reports with the State Climatologists. Given the historic cooperative relationship between the various State Climatologist and the NASS State Statistical Offices, this data should become available with reasonable timeliness.

The Mid-East Regional Weather Center also collects some daily weather data from the remaining objective yield states. However such data is not as complete as that which can be obtained from other sources.

More detailed cost information will be acquired in a four state semi-operational test in 1988. However, a tentative evaluation would indicate the additional costs of collecting and processing the weather data are quite small in comparison with the substantial potential benefits of a considerably more accurate corn forecasting model.

CONCLUSION AND RECOMMENDATIONS

Simulated operational evaluations of weather directed corn forecast models for August 1 predictions of average weight of grain per ear demonstrate that composites of selected models have the potential for providing substantially better forecasts than the current system.

We propose that NASS conduct a semi-operational test of this procedure in four states with the 1988 corn objective yield surveys. Such a test will provide further evaluation of the models, consideration of simplified models, and an evaluation of the weather data collection and key entry efforts required for an operational system.

The models evaluated in this report were defined from as few as 11 to no more than 16 years of data, up to and including the 1983 crop season. An additional four years of data (including the 1987 crop season) is now available. This data should be incorporated in a complete review of the models for all States. This review should begin with Minnesota and Michigan.

Further areas of research include possible simplification of the current modeling procedure for ear weight; as well as the use of weather variables with observations from the regular corn objective yield survey to provide more accurate (1) August 1 forecasts of the number of ears per acre, and (2) September 1 forecasts of ear weight. There is also potential for improving forecasts of such other objective yield survey crop components as wheat head weight, cotton boll weight, and soybean pods per plant.

APPENDIX

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LITERATURE REVIEW

One of the earliest scientific reports on the effect of weather on corn was a study by Lehenbauer (1913) which found a temperature of 32°C (90°F) as the optimum temperature for (vegetative) corn growth. This was followed by the first true yield forecast model, Wallace (1920). Subsequently, reports from Kiesselbach (1922), Hopper (1925), Alberts (1926), and Wolfe (1927) concluded that the date of silking is the most significant time for establishing a base point for corn maturity.

Hanna (1924) found that maize growth rates were correlated more closely with temperature than with several other factors. The development rates were curvilinearly related to temperature with maximum development at the optimum temperature. Above the optimum temperature the curve decreases drastically, rapidly approaching zero development.

Bair (1942) compared weekly temperatures (means and indices calculated according to Lehenbauer's tables) with net gains in dry weight during July and August in 1938 and 1939. Correlations were highly significant for 1939 (when there were several weeks of well below average temperatures), but were not significant for 1938.

Houseman (1942) found that an inch of rain occurring during any five day period near the end of July had the greatest benefit to corn yield. He also reported that higher than normal temperatures adversely affected corn yields more in August than in July and more in July than in June.

A later report by Kiesselbach (1950) states that (1) the period of several weeks prior to and including silking and fertilization is regarded as a critical period, especially in times of drought, and (2) combinations of high temperatures, low rainfall, low relative humidity, high wind velocity, and high evaporation rate are conducive to low yields. In particular, he found an average 6.75 bushel reduction in yield for each rise of a degree Fahrenheit in the mean seasonal (June-August) temperature at Lincoln, Nebraska.

Gilmore and Rogers (1958) developed a modified degree day method for determining the amount of time from planting to silking by ignoring maximum temperatures in excess of 86°F.

Chagnon and Neill (1967) cited Swanson and Jones (1966) as considering the period from July 18-August 3 as being critical for corn, and quoted Thompson (1963) as finding (1) that July temperatures were more highly correlated with Illinois yields than August temperatures, and (2) that the best single measure of the effect of weather on corn yield was the cumulative degrees above 90°F for July and August.

Runge (1968) determined that the maximum effect of temperature and rainfall on corn yield occurred over a two week period, starting two weeks before anthesis. He also determined that higher than normal temperatures (90 to 95^{o}F) may not be harmful to corn if adequate moisture is available.

Leeper, Runge and Walker (1974) developed an equation which attempted to relate soil moisture, temperature, and precipitation to yield. For a ten week period that starts 6 weeks before tasseling, the model uses the amount of plant available stored soil water at planting as well as both the sums and sums of squares of weekly precipitation and of the weekly average maximum daily temperatures during this period. However, an evaluation of this model for the 1969 to 1974 crop years by Runge and Keener (1978) found excessive prediction errors for all states.

Duncan (1975) states 'The question of how many potential kernels can develop on an ear, and how this number might be affected by environmental influences, has not been answered satisfactorily.'

Larson and Hanway (1977) state that the tasseling to silking period is particularly critical since silks must be pollinated before kernels can develop, and under severe stress conditions the cobs may be bare.

Stapper and Arkin (1979) cite Salter and Goode (1967) and Slabbers (1979) as having determined that water stress during the pollination period is the most important reason for grain yield decrease.

Soil Moisture Index Computations

The daily water requirement of corn, as defined by the Blaney-Criddle procedure, is a function of such factors as the length of day at a particular location, by the average daily temperature, and by what fraction of the growing season has elapsed. The length of day for any particular calendar day is determined by the geographic latitude of a particular site. The average daily temperature is computed as the average of the daily minimum and maximum temperatures. For any particular temperature level, daily water consumption is zero at emergence, increases gradually until anthesis (silking), and then declines until the plant is fully mature. State average (Crop Reporting District averages weighted by acres of corn for grain) temperatures, precipitation, median planting and silking dates, and latitudes) were used throughout.

Water requirements per unit area will be affected by the number of plants per unit area. Since there was a large increase in the number of plants per acre in each state, the water requirements from the Blaney-Criddle procedure for each year and State were multiplied by the value of (number of plants this year)/(average number of plants from the first year of the study for that State through 1983).

Daily soil moisture indices in this study were computed by the following algorithm:

Daily soil moisture index = Soil moisture index for the previous day) + (average precipitation for this day) - (water required for this day).

The average soil moisture holding capacity for each state was arbitrarily set at 10.0 inches of plant available water. While arbitrary, this value is small enough that it could, and occasionally did (in extreme drought conditions), drop to a minimum value of zero. At the same time, it was large enough that it did usually did not go that low. All ten states in the corn objective yield survey region were found to receive at least 10.0 inches of precipitation between the end of the preceding growing season and the start of the current season. Therefore, the soil moisture index was set at this value at the beginning of each crop growing season.

VARIABLE DEFINITIONS

SILK_DAY -- For each year, the Julian date by which 50 percent of the corn in a state starts to show silks.

All the variables except SILK_DAY and DDG88F6 end in a number from 1 to 5. This last numeric digit represents the time period used to calculate the weekly sum in the model. Time period 1 is the fourth week (28 to 22 days) before the median silking date; time period 2 is the third week (21 to 15 days) before the median silking date; time period 3 is the second week (14 to 8 days) before the median silking date, time period 4 is the week (7 to 1 days) before the median silking date; and time period 5 is the week after the median silk date. For example, AVTEMP1 is the average (average of daily minimum and maximum temperatures) daily temperature for the first time period, which is the fourth week before the median silk date.

(AVTEMP1-AVTEMP5) -- The average (average of daily minimum and maximum temperatures) daily temperature for time periods 1 through 5, respectively.

(DDG88F1 - DDG88F5) -- The average number of degrees that the maximum daily temperature exceeded 88°F for time period 1 through time period 5.

DDG88F6 -- The average number of degrees that the maximum daily temperature exceeded 88°F for time period 6 which is two weeks after median silk date.

(DDL88F1 - DDL88F5) -- The average number of degrees the the maximum daily temperature fails to reach 88°F for time periods 1 through 5, respectively.

(DIFTMP1 - DIFTMP5) -- The average daily difference between the daily minimum and maximum temperatures for time periods 1 through 5, respectively.

(WKLYSMB1 - WKLYSMB5) -- The average daily soil moisture index for time periods 1 through 5, respectively.

DDLSMB4 -- The product of DDL88F4 and WKLYSMB4.
DDLSMB5 -- The product of DDL88F5 and WKLYSMB5.

Table A-1. Root mean square forecast errors (RMSFE) and relative gains[a] (RG) for the recommended models as compared with the operational survey forecasts, 1979-86.

State	Operational Survey August 1	Operational Survey September 1	August 1 Weather Models	Relative Gain August 1	Relative Gain September 1
	lb/ear	lb/ear	lb/ear	percent	percent
Illinois	.0465	.0305	.0234	50	23
Indiana	.0409	.0278	.0228	44	18
Iowa	.0498	.0359	.0306	34	15
Michigan	.0243	.0176	.0211	13	-20
Minnesota	.0287	.0251	.0214	26	15
Missouri	.0741	.0585	.0458	38	22
Nebraska	.0402	.0390	.0257	36	34
Ohio	.0299	.0310	.0216	28	30
South Dakota	.0333	.0327	.0252	24	23
Wisconsin	.0236	.0204	.0192	19	6
Ten State Av	.0411	.0319	.0265	36	17

[a] Relative gain was calculated as [1 - (Weather model RMSFE) / (Operational Survey RMSFE)].

Table A-2. Number of cooperative weather stations, by state, July 1986

State	Total Stations	Precipitation Only
Illinois	153	49
Indiana	103	16
Iowa	163	35
Michigan	154	35
Minnesota	167	38
Missouri	170	46
Nebraska	216	96
Ohio	167	68
South Dakota	141	30
Wisconsin	169	36

Figure A-1. Variables for August 1 Weather/corn ear weight forecast models: (1) without soil moisture, (2) with soil moisture, and (3) late growing season (3), by State

```
             ***************************     **************
             *MINNESOTA   *WISCONSIN   *     *MICHIGAN    *
             *          1 *          1 *     *           1*
             * DDG88F2    * DDG88F1    *     *  SILK_DAY  *
             * DIFTMP4    * DDG88F2    *     *            *
**************            * AVTEMP1    *     *            *
*SOUTH DAKOTA*............*............*     *............*
*          1 *          2 *          2 *     *           2*
* DDG88F3    * DDGSMB2    * DDGSMB2    *     *  SLOPE13   *
*            * DIFTMP4    * DDG88F1    *     *  DDLSMB3   *
*............*............*............*     *............*
*          2 *          3 *          3 *     *           3*
* SLOPE14    * DIFTMP4    * DDG88F1    *     *  SLOPE13   *
* DDG88F3    * AVTEMP2    * DDG88F2    *     *  AVTEMP3   *
*............***************************************************
*          3 *IOWA        *ILLINOIS    *INDIANA     *OHIO      *
* DDGSMB3    *          1 *          1 *          1 *         1*
*            * DDL88F5    * DDG88F3    * DIFTMP2    * SILK_DAY *
*            * DIFTMP2    * AVTEMP5    * DDG88F3    * DIFTMP2  *
************** DDG88F2    *            * AVTEMP3    *          *
*NEBRASKA    *............*............*............*..........*
*          1 *          2 *          2 *          2 *         2*
* DDG88F5    * SLOPE13    * DDGSMB3    * WKLYSMB3   * DIFTMP2  *
* DIFTMP2    * DIFTMP5    * DDGSMB4    * DDLSMB4    * SILK_DAY *
*............*............*............*............* WKLYSMB5 *
*          2 *          3 *          3 *          3 *..........*
* WKLYSMB4   * DIFTMP2    * DDG88F3    * WKLYSMB3   *         3*
* DIFTMP2    * DDG88F2    * AVTEMP4    * DDG88F3    * SLOPE12  *
* WKLYSMB2   **************            * AVTEMP3    * SLOPE13  *
*............*MISSOURI    *            *            * SILK_DAY *
*          3 *          1 *            *            ************
* SLOPE12    * AVTEMP5    *            **************
* DIFTMP2    * DDG88F5    *            *
*            * DDG88F6    **************
**************............*
             *          2 *
             * DDG88F5    *
             * DDLSMB5    *
             * DDG88F6    *
             *............*
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